The Collider Scenario

The RHIC design goals can be achieved in different ways. An important choice in the RHIC design was the utilization of short bunches colliding head-on to enhance the luminosity while keeping the average current and stored beam energy low. Formation of the bunches occurs prior to injection. The existing accelerator complex at BNL consisting of Tandem Van de Graaff accelerators, the Booster synchrotron, and the Alternating Gradient Synchrotron (AGS), will serve as the injector for the RHIC. The sequence of steps in the chain of accelerators is shown in Fig. 2 for the prototypical example of gold ions.

The existing upgraded Tandem Van de Graaff accelerators will serve for the initial ion acceleration. When upgraded, the second Tandem will be available in parallel, so that a spare source of particles will exist. It is planned that a two-stage operation be employed with the negative ion source at ground potential. The negative ions, with charge -1, are accelerated from ground to +15 MV potential. They pass through a stripping foil in the high voltage terminal yielding partially stripped ions, with a positive charge, Q_T, which is a function of the element being accelerated. The partially stripped ions are accelerated back to ground potential, increasing their energy by $15 \times Q_T$ MeV. For the prototypical example of gold beams, the ions exit the Tandem at the kinetic energy of 1 MeV/u and with $Q = +12$ charge state.

Exiting from the Van de Graaff, the ions are further stripped to charge state +32. They then will traverse a long (~ 550 m) heavy ion transfer line to the AGS (HITL), continue in a new, shorter section by-passing the AGS (HTB) and proceed to be injected into the Booster synchrotron. The beam from the Tandem will be stacked in both horizontal and vertical betatron space by adding linear coupling to the Booster lattice. The 700 µsec Tandem pulse yields 45 Booster turns for gold. The stacking/capture efficiency is about 50%, so for gold, the 4.5×10^9 ions from Tandem yield 2.2×10^9 ions accelerating in the Booster.

The Booster can accelerate this beam to 0.65 T in less than 100 ms. A single rf system (two cavities) operating on the 8th harmonic of the revolution frequency provides the accelerating voltage over this range (frequency swing from 530 kHz to 5 MHz). The eight bunches are merged to four in the Booster just at extraction, where their kinetic energy is 95 MeV/u. In the Booster-to-AGS (BtA) transfer line, the ions are stripped once again by a 23 mg/cm^2 foil to charge state +77 (60% stripping efficiency, only K-shell electrons remaining) and then enter the AGS.

Four such Tandem/Booster cycles, occurring at a 5 Hz repetition rate, fill the circumference of the AGS using 600 ms of the AGS repetition period. The bunches are injected into matching AGS rf buckets (h = 16). After the fourth transfer, the beam is accelerated enough to allow a merge from 16 to 8 bunches, accelerated to full energy (10.8 GeV/u for gold) and is merged again from 8 to 4. At this point in the acceleration cycle, all of the particles from a single Booster acceleration batch are contained in a single AGS bunch. With 75% acceleration efficiency (Booster and AGS together), this bunch would contain 1×10^9 ions [(75% acc eff)×(60% BtA foil stripping)×(2.2×10^9)]. This level of acceleration efficiencies has been demonstrated.

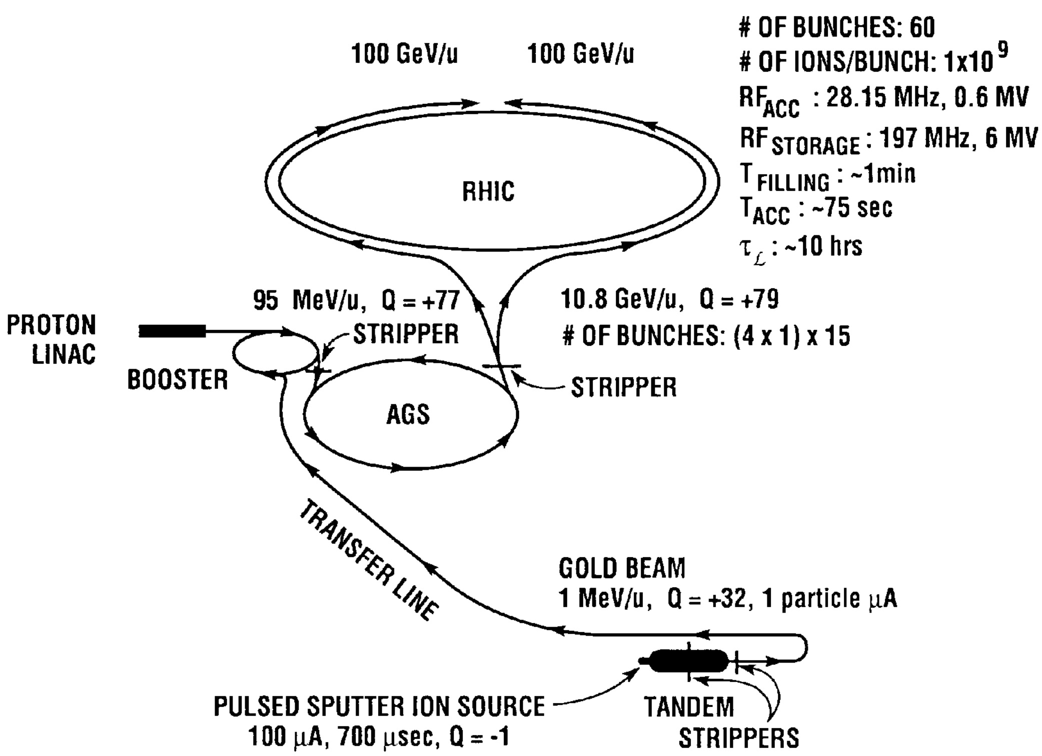

Fig. 2. RHIC Acceleration Scenario for gold.

Finally, the beam is fast extracted into the existing AGS to RHIC (AtR) transfer line tunnel using a new magnet system installed there. A final stripping from +77 to +79 takes place at the start of this line. For protons the acceleration strategy is simplified, the merges are unnecessary, since intensity is not a problem. For heavy ion and proton cycles, the final kinetic energies (10.8 GeV/u and 28.3 GeV respectively) correspond to a peak AGS *B*ñ of 100 Tm.

The project includes the construction of a beam transfer line between the AGS and the collider rings. This new beam transport system uses conventional room temperature magnets, some of which already exist from procurements for the former CBA project, and it employs a magnetic septum magnet and fast kicker system of well-proven design to deposit the beam vertically onto the injection closed orbit.

A total of nominal 60 bunches are injected into each collider ring in bunch-to-bucket fashion. The AGS extraction system will allow single-bunch transfer of the four AGS bunches into one of the two collider rings. This cycle is repeated 2×15 times in order to fill each collider ring with the 60 bunches. Filling both rings requires about 1 minute. Minimizing the filling time is important in order to prevent bunch area dilution due to intrabeam scattering, which in the case of gold increases the energy spread by 10% in 2 min at injection. Present operational results project a gold intensity of ~ 1×10^9 ions/bunch or a total of ~ 6×10^{10} ions in the 60 bunches in each ring. For the lightest ions, hydrogen and deuterium, approximately 10^{11} ions/bunch can be stored in the collider as presently designed. The nominal number of ions per bunch transferred to the collider is given in Table 2. The intensity was estimated from Tandem currents after allowing for some losses in the Booster and the AGS. The maximum number of protons in the AGS is larger by an order of magnitude, however, the design number of 10^{11} protons/bunch is adequate for heavy ion physics.

Projected beam parameters, i.e. bunch area *S* and normalized transverse emittance $å_N$, at RHIC injection are given in Table 2. The beam parameters for ions from the Tandem are taken to be the same for all species, i.e 0.5 eV·s/u and 10 ð mm ·mrad. Those for protons are different, with a larger emittance, i.e. 20 ð mm.mrad, since they come from a different source. The bunch area containing ~ 95% of the beam population, *S*, is defined by $S = 6ð\, ó_ô\, ó_E$ where $ó_ô$ is the rms bunch length in units of time and $ó_E$ the rms energy spread. Correspondingly, the normalized emittance, is defined by $\varepsilon_N = (â\ ã)\,\varepsilon = (â\ ã)\,6ð\,ó^2_{H,V}/â_{H,V}$ where $ó_{H,V}$ is the rms beam width or height and $â_{H,V}$ the horizontal or vertical amplitude lattice function. By local convention, the energy spread is quoted as $\pm\sqrt{6}\,ó$ and the (total) bunch length as $2\sqrt{6}\,ó$.

The beam parameters are quoted for a typical set of ion species in order to illustrate the variation of the collider performance over the entire mass range. The Tandem Van de Graaff source is capable of delivering many other elements, most of them in adequate intensity. In fact, the choice of ^{16}O and ^{28}Si may entail operational difficulties due to the mass-to-charge ratio being $A/Z = 2$, potentially leading to beam contamination with lighter fragments of equal rigidity. Since this problem could be circumvented by the use of isotopes or different elements such as ^{11}B and ^{35}Cl, the discussion is limited here to the few illustrative examples of Table 2.

The bunch separation in the collider ring is 64 m, and this corresponds to a rise time of ~ 190 nsec for the RHIC injection kickers. An upgrade option is to stack 72, 90 or 120 bunches in RHIC, and this will require a kicker with 95 nsec rise time. The kicker will be designed to start with this faster rise-time. The injection kicker will allow the transfer of single bunches from the AGS, which will be the standard beam transfer mode.

The adoption of beam transfer from the AGS to RHIC in the single-bunch mode allows considerable freedom in the choice of the harmonic number and rf frequency in RHIC. The choice of $h = 360$ provides the maximum flexibility in the filling pattern and thus bunch spacing to suite experimental needs. The bunches are captured in stationary buckets of the so-called acceleration rf system operating at ~ 28.15 MHz, corresponding to a harmonic $h = 360$. The acceleration rf system has 2 cavities per ring capable of providing a total of 600 kV peak voltage. In order to avoid bunch area dilution, it is essential to match the shape of the bunches from the AGS to the shape of the buckets of the collider rf. The harmonic chosen together with the rf voltage available provide adequate bucket area in the collider but require bunch rotation in the AGS prior to the bunch transfer for proper matching. The beams are injected into RHIC at 300 kV for gold and heavy ions, but 170 kV for protons. The nominal bunch parameters at injection into the collider are quoted in Table 2.

After injection of the beam, the rf voltage can be adjusted adiabatically to optimum values for acceleration and the crossing of the transition energy (nominally 300 kV for the prototypical gold beam). In order to avoid bunch area dilution at transition, a ã-transition jump will be executed, limiting the bunch area growth to 0.7 eV·s/u. Proton beams are injected above transition and need no special gymnastics.

After having reached the operating kinetic energy corresponding to a *B*ñ = 839.5 T·m, which takes about 1 min, the bunches are transferred from the acceleration (28.15 MHz) to the storage rf system at 197 MHz. The harmonic number of the storage rf is $h = 360{\times}7 = 2520$, resulting in a bucket length of 1.52 m. This frequency was chosen in order to limit the growth of the bunch due to intrabeam scattering to an rms bunch length of <25 cm. The resulting rms diamond length is less than ~18 cm.

With a bunch area after transition of 0.7 eV·s/u, the length of a gold bunch is before rebucketing longer than the storage bucket length. Shortening of the bunch is necessary for all ion species and is accomplished by a non-adiabatic bunch rotation in the acceleration system. Each of the RHIC rings has 3 storage system cavities and shares additional 4 common cavities with the other ring for a total voltage of 6 MV. The 3 cavities provide the marginal voltage required to accept the shortened bunches. After transfer, the storage rf voltage is adiabatically raised to its maximum value available and kept constant during the storage cycle.

During storage, the bunches will grow due to intrabeam scattering. The voltage required to contain gold beams during a 10 hour storage period depends on the initial emittance and acceptable losses. With the beam emittances of 0.7 eV·s/u and 10 ð mm·mrad for gold at the beginning of the storage cycle, the 197 MHz rf system with a total of 6 MV/turn will be capable of limiting the bunch length growth with less than 40% particle loss during the 10 hour lifetime. The projected beam parameters at the start and end of the storage cycle are also listed in Table 2.

The stored beam energy is about 200 kJ per ring, small enough to be aborted onto an internal beam dump at the end of the storage period or in case of equipment malfunction. The beam will be dumped in a single turn (13 μsec) by activating the ejection kicker which deflects the beam horizontally onto a dump block. In order to facilitate the beam abort design, a gap of ~ 1 μsec corresponding to 4 missing bunches will be provided.

Operation of the collider and achievement of full performance will require continuous monitoring of many beam characteristics, and appropriate beam instrumentation will be provided. A central control system will allow the control of, and communication among, the various collider systems.

The major parameters of the collider are listed in Table 3. The accelerator systems to be constructed for the RHIC project will be defined in greater detail in the subsequent sections of this Design Manual.

Table 2. General Beam Parameters for the Collider

Element	Proton	Deuterium	Oxygen	Silicon	Copper	Iodine	Gold
Atomic Number Z	1	1	8	14	29	53	79
Mass Number A	1	2	16	28	63	127	197
Rest Energy (GeV/u)	0.93827	0.93781	0.93093	0.93046	0.92022	0.93058	0.93113
Injection:†							
Kinetic Energy (GeV/u)	28.3	13.7	13.7	13.7	12.6	11.3	10.8
Energy, ã	31.2	15.6	15.7	15.7	14.5	13.1	12.6
Norm. Emittance (ðmm·mrad)	20	10	10	10	10	10	10
Bunch Area (eV·s/u)	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Bunch Length (m)	2.58	4.1	4.1	4.1	4.6	5.32	5.62
Energy Spread ($\times 10^{-3}$)	±1.26	±1.63	±1.63	±1.63	±1.59	±1.52	±1.49
No. ions/Bunch ($\times 10^{9}$)	100	100	8.3	5.6	2.7	1.5	1.0
*Top Energy, @ transfer:**							
Kinetic Energy (GeV/u)	250.7	124.9	124.9	124.9	114.9	104.1	100.0
Energy, ã	268.2	134.2	135.2	135.3	124.5	112.9	108.4
rms Bunch Length (m)	0.10	0.17	0.17	0.17	0.18	0.19	0.19
Energy Spread ($\times 10^{-3}$)	±0.83	±1.35	±1.35	±1.35	±1.41	±1.46	±1.49
*Top Energy, @ 10 h:**							
rms Bunch Length (m)	0.14						0.22
Energy Spread ($\times 10^{-3}$)	±1.25						±1.78
Norm. Emittance (ðmm·mrad)	29						43
Bunch Area (eV·s/u)	1.2						1.1

†Acceleration rf System $h = 360$, $V_{rf} = 300$ kV, except 170 kV @ p
*Storage rf System $h = 2520$, $V_{rf} = 6$ MV

Table 3. Major Parameters for the Collider

Kinetic Energy, Injection-Top (each beam), Au	10.8-100	GeV/u
protons	28.3-250	GeV
Luminosity, Au-Au @ 100 GeV/u & 10 h av.	~2×10^{26}	cm^{-2} sec^{-1}
No. of bunches/ring	60	
No. of Au-ions/bunch	1×10^{9}	
Operational lifetime Au @ ã > 30	~10	h
Diamond length	18	cm rms
Circumference, 4-3/4 C_{AGS}	3833.845	m
Beam separation in arcs	90	cm
Number of crossing points	6	
Free space at crossing point	±9	m
Beta @ crossing, horizontal/vertical	10	m
low-beta insertion	2	m
Crossing angle, nominal (maximum)	0 (< 1.7)	mrad
Betatron tune, horizontal/vertical	28.19/29.18	
Transition Energy, ã$_T$	22.89	
Magnetic Rigidity, *B*ñ: @ injection	97.5	T·m
@ top energy	839.5	T·m
Bending radius, arc dipole	242.781	m
No. of dipoles (192/ring + 12 common)	396	
No. of quadrupoles (276 arc + 216 insertion)	492	
Dipole field @ 100 GeV/u, Au	3.458	T
Arc dipole length, effective	9.45	m
Arc Dipole length, physical	9.728	m
Dipole current	5.093	kA
Arc quadrupole gradient	~71	T/m
Arc quadrupole length, effective	1.11	m
Coil i.d. arc magnets	8	cm
Beam tube i.d.	6.9	cm
Operating temperature, Helium refrigerant	< 4.6	K
Refrigeration capacity at 4 K	24.8	kW
Cooldown time, entire system	~7	d
Vacuum, warm beam tube sections	~7×10^{-10}	mbar
Filling mode	Bunch-to-bucket	
Filling time (each ring)	< 1	min
Injection kicker strength (95 nsec)	~0.18	T·m
Beam stored energy	~200	kJ
rf voltage, *h*=360	600	kV
rf voltage, *h*=2520	6	MV
Acceleration time	75	sec